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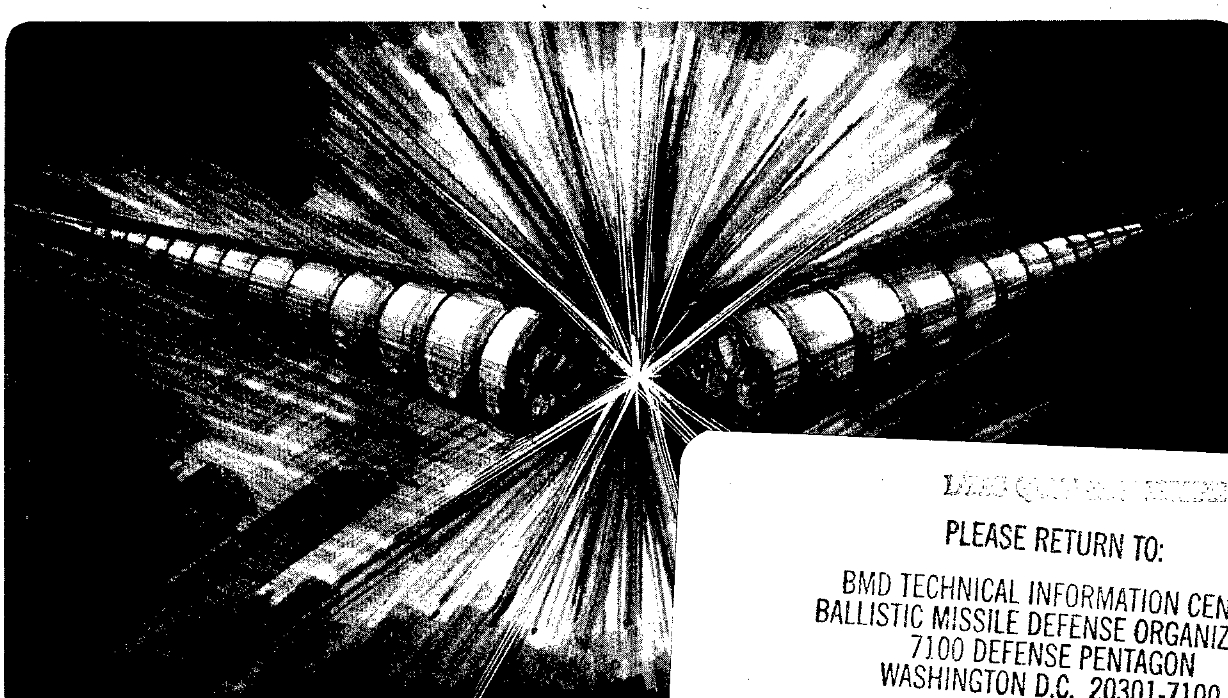
TEMPERATURE RISE PRODUCED BY SYNCHROTRON RADIATION

Edward P. Lee

August 1981



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Technical Report of the Betatron Design Study

TEMPERATURE RISE PRODUCED BY SYNCHROTRON RADIATION*

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August 1981

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The temperature rise produced by synchrotron radiation incident on the vacuum chamber wall of a betatron is evaluated for a general acceleration cycle.

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Temperature Rise Produced by Synchrotron Radiation*

by
Edward P. Lee

Synchrotron radiation heats a narrow band of the vacuum chamber wall in the orbital plane. The associated temperature rise of the surface, which depends sensitively on the system parameters and operating mode, has been estimated[1] for a high-energy betatron under study to be only on the order of 60°C [for a single pulse, and somewhat higher for a series]. Therefore no particular allowance in design need be made unless long periods of coasting (say 10 msec) at high energy are contemplated. The general formulations of this analysis are given here primarily to aid in any reevaluation of the heating and to correct some errors made in a previous report.[2] Details of specific examples are given in reference (1).

The net power radiated by the beam is[3]

$$P = (8.85 \times 10^7 \text{ watts}) \quad \frac{E_{GeV}^4 \, I_{kA}}{R} \quad ,$$

where E is particle energy, I is beam current, and R is the radius of curvature in meters. This power falls in a band of width A on the wall at radius $R_w > R$, with flux

$$W = \frac{P}{2\pi R_w A} = (1.41 \times 10^5 \text{ watt/cm}^2) \frac{E_{GeV}^4 \, I_{kA}}{R \, R_w \, A_{cm}} \quad .$$

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The temperature rise (ΔT) in the wall can be determined for any specified flux W(t) by solving the heat diffusion equation. In the following we assume the radiation is normally incident and totally absorbed. The material is aluminum, which has properties

thermal conductivity	$K = 2.52\ \mathrm{w/^\circ C\text{-}cm}$,
specific heat	$C = .95\ \mathrm{J/^\circ C\text{-}gm}$,
density	$\rho = 2.7\ \mathrm{gm/cm^3}$.

Any change in these assumptions can be incorporated into the derived results with a single multiplicative factor.

The heat diffusion equation

$$\frac{C\rho}{K}\ \frac{\partial \Delta T}{\partial t} = \frac{\partial^2 \Delta T}{\partial x^2}$$

is to be solved subject to initial condition $\Delta T(t{=}o) = 0$ and the boundary condition on incident flux

$$W(t) = -K\ \frac{\partial T}{\partial x}\ (x{=}o)$$

Solution by the Laplace transform method yields

$$\Delta\ T = \frac{1}{2\pi i} \int_{-i\infty}^{+i\infty} ds\ f(s) e^{st - a\sqrt{s}\,x} \quad ,$$

where $a^2 \equiv C\rho/K$ and

$$f(s) = \int_0^\infty dt\ \frac{e^{-st}}{\sqrt{s}}\ \frac{w(t)}{Ka} \quad .$$

We are interested only in ΔT evaluated at $x = o$, where it is highest.

Two simple cases of W(t) which are useful for quick estimates can be worked out using the formal solution:

<u>Case 1</u>:

$$W = \begin{cases} Wo, & o < t < to, \\ o, & t > to. \end{cases}$$

$$\Delta\ T\ (x{=}o) = \frac{2\ Wo}{\sqrt{\pi\ CK\rho}} \cdot \left\{ \begin{matrix} \sqrt{t}\ , & t < to \\ (\sqrt{t} - \sqrt{t - to})\ , & t > to \end{matrix} \right\}$$

<u>Case 2</u>:

$$W = W_o \left(\frac{t}{to}\right)^n ,$$

$$\Delta T(x{=}0) = \frac{2\ Wo}{\sqrt{\pi CKP}}\ \frac{t^{n+1/2}}{to^m} \left[\frac{\Gamma\ (n+1)\ \sqrt{\pi}}{2\Gamma(n+3/2)}\right]$$

For the particular case n= 9/2, corresponding to a linear energy ramp $E \propto t$ and $A \propto t^{-1/2}$, we have for the numerical factor

$$\left[\frac{\Gamma(11/2)\ \ \sqrt{\pi}}{2\Gamma(12/2)}\right] = \frac{63\pi}{512} = .3866 \quad .$$

The more complicated situations involving periods of coasting and acceleration are not conveniently treated by the transform method. However, a simple Green's function exists which makes this problem numerically tractable. We note that for an impulsive flux $\delta W = U\delta\ (t-t')$, that

$$f(s) = \frac{U}{Ka}\ \frac{e^{-st}}{\sqrt{s}}$$

the inverse transformation is readily evaluated to be

$$\Delta T(x=o) = \frac{1}{2\pi i}\int ds\, \frac{e^{s(t-t')}}{\sqrt{s}}\, \frac{U}{Ka}$$

$$= \frac{U}{Ka}\, H(t-t')\, \frac{(t-t')^{-1/2}}{\Gamma(1/2)} \quad ,$$

where H is the unit step. To get the general response we let $U \to W(t')\,dt'$ to obtain

$$\Delta T(x=o) = \int_0^\infty dt'\, W(t')\, \frac{H\,(t-t')\,(t-t')^{-1/2}}{Ka\,\Gamma\,(1/2)} \quad ,$$

$$= \frac{1}{\sqrt{\pi CK\rho}} \int_0^t dt'\, \frac{W\,(t')}{\sqrt{t-t'}} \quad .$$

A very useful form for numerical evaluation is

$$\Delta T(x=o) = \frac{2\, Wo \sqrt{to}}{\sqrt{\pi CK\rho}}\, F \quad ,$$

where $Wo = W\,(to)$ and F is the numerical factor (of order unity)

$$F = \frac{1}{2} \int_0^{to} \frac{dt}{t_o}\, \frac{W(t)/Wo}{\sqrt{1 - t/to}} \quad .$$

References

(1) LLNL Report, UCRL 15316-3.

(2) LLNL Report, UCRL 15316-2.

(3) J.D. Jackson, Classical Electrodynamics, 1962 Wiley 472.